

Latest Results from K2K^a

Takanobu Ishii

(for the K2K Collaboration)

Institute of Particle and Nuclear Studies, KEK, Tsukuba, Japan

The KEK-to-Kamioka long-baseline neutrino experiment (K2K) has begun its investigation of neutrino oscillation, and has established the method of a long-baseline neutrino experiment. From the first 100 days of data-taking, a deficit of ν_μ in the 1-GeV energy region after 250-km flight was observed at the 90% significance level.

1 Introduction

The possible existence of neutrino masses is the first signal beyond the standard model, which suggests grand unification. The KEK-to-Kamioka long-baseline neutrino experiment (K2K)¹ is motivated by the atmospheric neutrino anomaly found by the Kamiokande experiment². One possible explanation of the anomaly is neutrino oscillation. Later, the Super-Kamiokande (SK) group confirmed the deficit of upward-going atmospheric ν_μ , and announced evidence for the oscillation of atmospheric neutrinos³ with a difference of the squared masses, $\Delta m^2 \sim 3 \times 10^{-3} \text{eV}^2$, and the mixing parameter, $\sin^2 2\theta \sim 1$. For a neutrino energy of $E_\nu (\text{GeV})$ and a flight length of $L (\text{km})$, the oscillation probability is expressed by the following formula in a two-flavor approximation:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2 \frac{1.27 \Delta m^2 \cdot L}{E_\nu}. \quad (1)$$

In order to pin down a small Δm^2 , we need a long baseline. K2K aims to establish neutrino oscillations in the ν_μ disappearance mode and in the ν_e appearance mode, with a well-defined flight length and a well-understood flux of a pure ν_μ beam.

2 Experimental Setup

K2K uses the SK as a far detector, which is situated 250 km from KEK. It is a 50 kton water Cherenkov detector, which is divided into an inner part and an outer part. The inner part is used as a target and

^aTalk presented at the XXXVIth Rencontres de Moriond "Electroweak Interactions and Unified Theories", Les Arcs, Savoie, France, March 10-17, 2001.

to measure the neutrino interactions, while the outer part is used to veto incoming activities. The background for the K2K experiment is atmospheric neutrinos of about 8 events/day, which can be reduced by a factor of 10^{-6} by employing a timing window.

The setup at the near site is shown in Fig. 1. Every 2.2 sec, a 12-GeV proton beam is fast-extracted from the KEK proton synchrotron (PS), making a $1.1\text{-}\mu\text{sec}$ spill structure. The designed intensity is 6×10^{12} protons/spill. Downstream of the arc where the proton beam is bent to the SK direction, a pair of horn magnets operating at 250 kA is located. The first horn magnet incorporates a pion production target comprising a 66-cm-long aluminum cylinder with a 30-mm diameter. The horn system focuses positive pions and enhances the neutrino flux by a factor of about 20. The beam line is aligned toward SK using the global positioning system (GPS). The accuracy of the GPS survey is better than 0.01 mrad and the accuracy of the civil construction is better than 0.1 mrad. For a long-baseline experiment, beam monitors are indispensable. We have a pion monitor just after the 2nd horn magnet, a muon monitor behind the beam dump, which is located most downstream of the 200-m decay tunnel where the pions decay to ν_μ and muons, and a set of near neutrino detectors at 300 m from the pion production target.

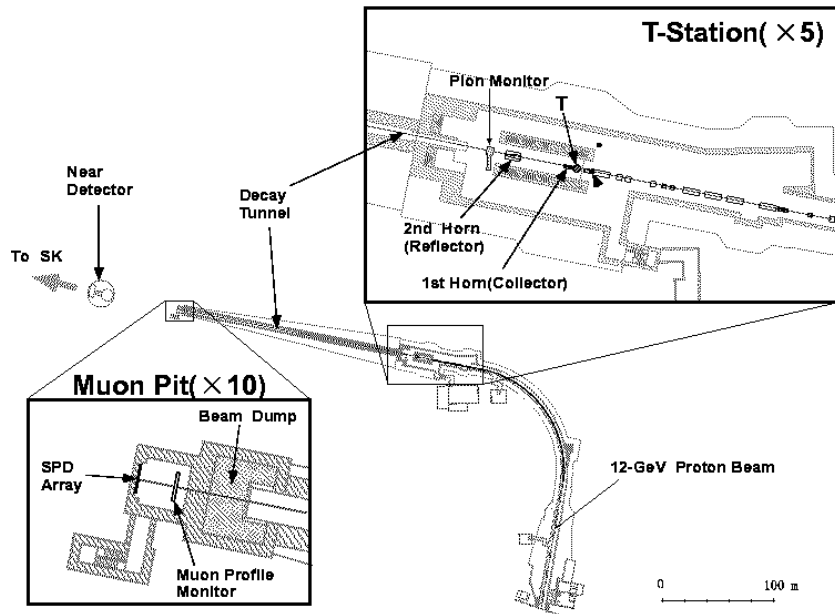


Figure 1: Near site setup at KEK.

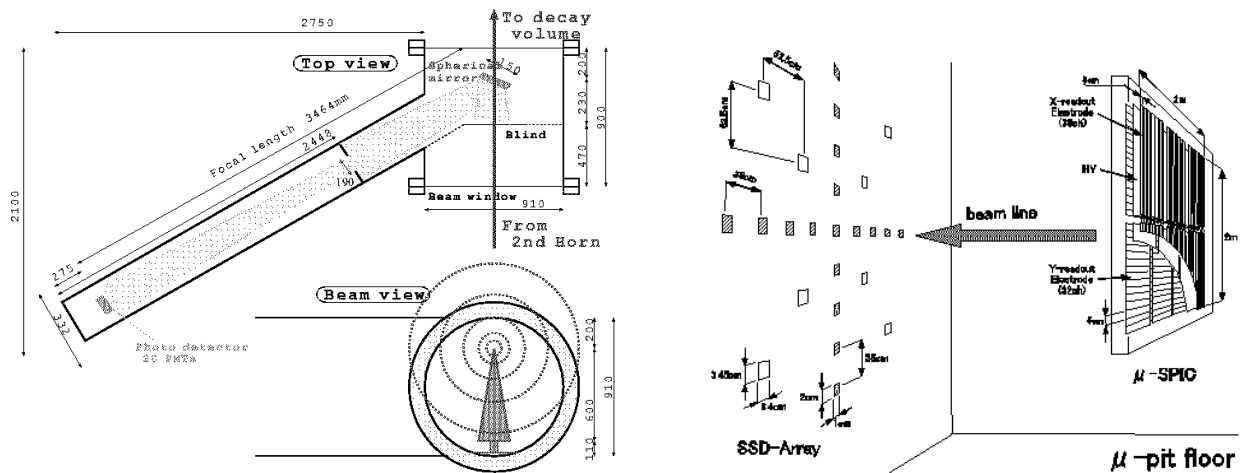
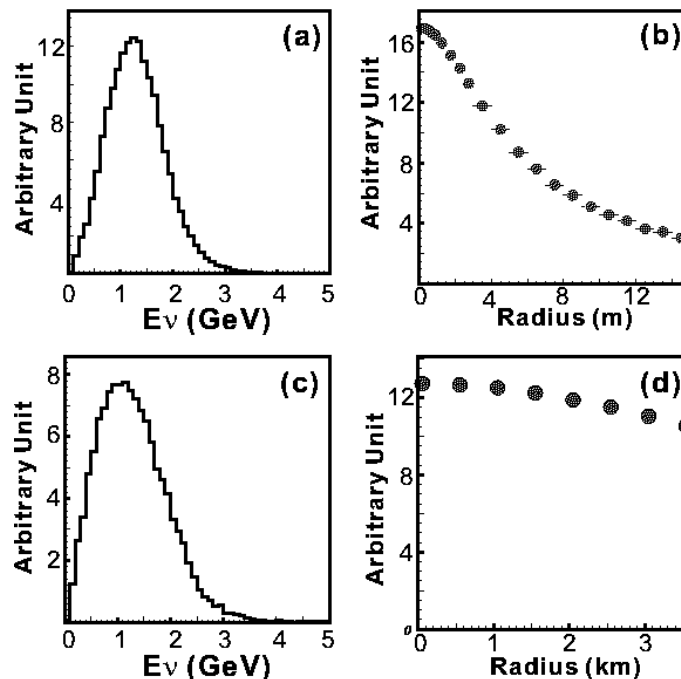
The neutrino spectra and the radial distributions at the near site and the far site from MC calculations are shown in Fig. 2. At the far site, the flux is almost constant up to 3 mrad (~ 750 m). This is the requirement of beam pointing. As for the spectra, there is a difference between far and near, making a simple extrapolation impossible. The pion monitor is used to deal with this fact.

The pion monitor⁴ measures the momentum and angular distributions of pions, which are the source of neutrinos. Once we know the pion momentum and angular distributions, we can calculate the neutrino flux at any distance. As a result, we can obtain the far-to-near flux ratio reliably. As shown in Fig. 3(Left), the pion monitor is a gas Cherenkov detector, which measures the Cherenkov ring of pions. It is occasionally put in the beam line. A pie-shaped spherical mirror focuses photons onto a PMT array located at the focal plane. The photon distribution on the PMT array is a superposition of slices of the Cherenkov rings from pions of various velocities and angles. Measurements are made at several indices of refraction. The pion two-dimensional distribution of momentum versus angle is derived by unfolding the photon distribution data at various indices of refraction. In order to avoid background from 12-GeV protons which have not interacted in the target, the pion monitor is sensitive to pion momentum higher than 2 GeV, corresponding to a neutrino energy higher than 1 GeV.

The muon monitor measures the muon profile and intensity. Since the muons are the decay partners of the neutrinos from the pions, muon measurements give information on the neutrino beam

direction and intensity. Since the rate of the muon monitor is high, it can measure the beam stability on a spill-by-spill basis. The beam direction is tuned by monitoring the muon profile at the muon monitor. As shown in Fig. 3(Right), the muon monitor consists of a segmented ionization chamber and a silicon pad detector array.

3 Results



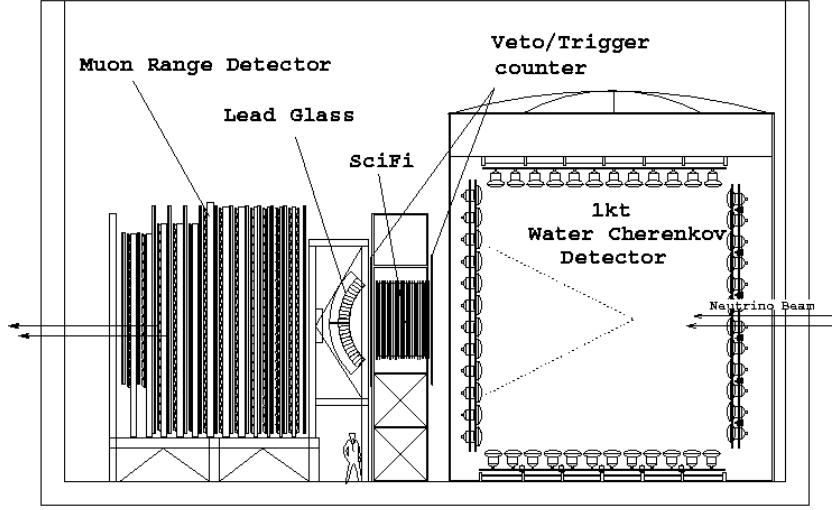


Figure 4: Near neutrino detectors.

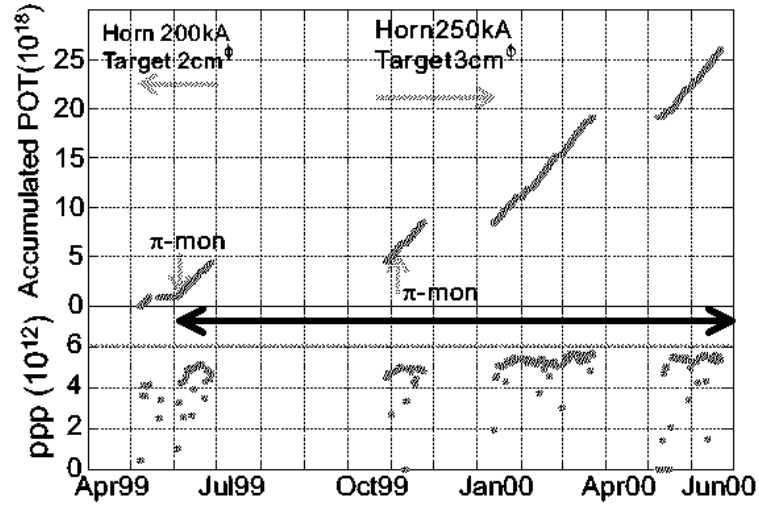


Figure 5: History of the beam delivery.

monitor measurements. The 1kt is used for normalizing the event numbers at the near site. Since the 1kt is a miniature of SK, we can expect the least systematic error in calculating the expected number at SK. By utilizing iron as the target, MRD gives a high event rate, which is suitable for monitoring the neutrino beam direction, intensity and spectrum. The SCIFI is used to study the neutrino interaction in detail.

The history of the beam accumulation is shown in Fig. 5. After an engineering run, we started data taking in June, 1999. The design intensity has been almost achieved. By June 2000, 2.6×10^{19} protons have been injected onto the target. Among this number, 2.29×10^{19} have been used for the analysis.

The neutrino beam direction is monitored by the MRD. Vertex distributions of MRD events in the horizontal and vertical directions are shown in Fig. 6(Left), which gives the neutrino beam profile. The center of the profile gives the neutrino beam direction. The beam is well directed to SK. The center of the profile is plotted in Fig. 6(Right) as a function of time for the horizontal direction and for the vertical direction. The beam has been pointed to SK within ± 1 mrad during the experimental periods.

The stability of the beam direction is also monitored by the muon monitor. The data show that the beam has been directed to SK within ± 1 mrad spill-by-spill during all data-taking periods.

The stability of the event rate is measured by the MRD (Fig. 7). The event rate normalized to the proton intensity has been stable within the statistical error. The slight difference in June, 1999, is due to a different horn current and a different target size.

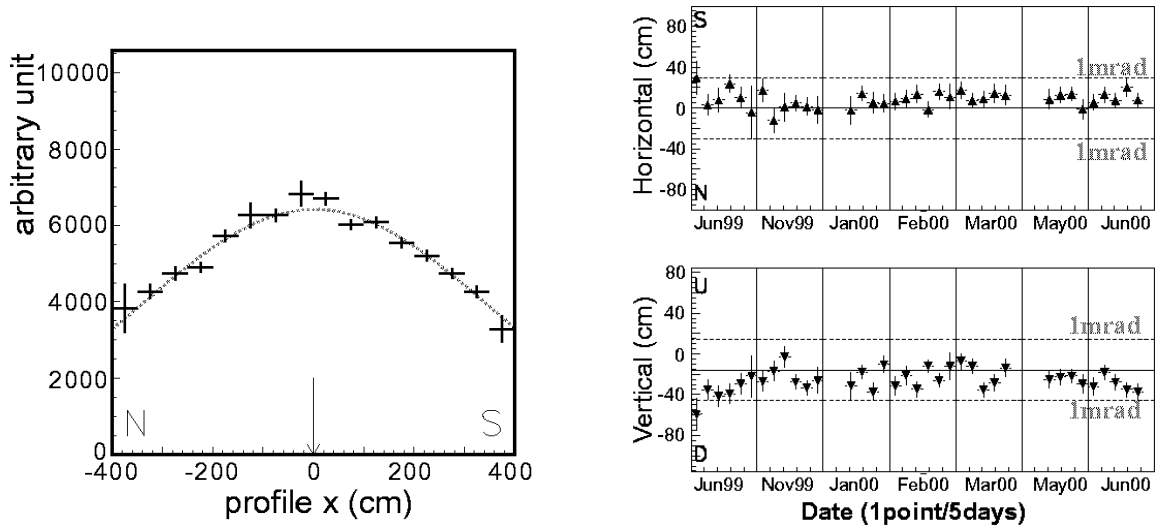


Figure 6: (Left) Beam profile. The points are measured data by MRD and the curve is a fitted Gaussian function. (Right) Stability of the profile center during the experimental periods.

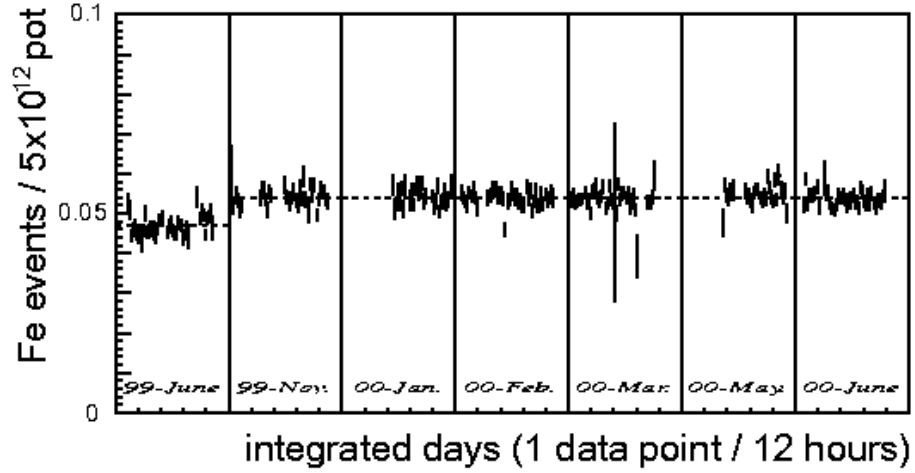


Figure 7: Stability of the event rate measured by MRD.

The muon energy and angular distributions are also continuously monitored. They are shown in Fig. 8 for each one-month period. These figures show no change in the energy and angular distributions, implying that the neutrino energy spectrum has been stable throughout these periods.

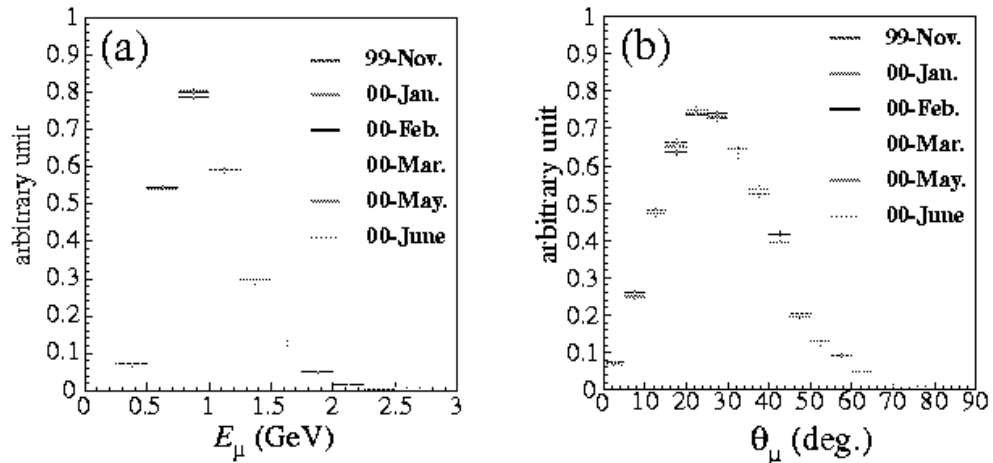


Figure 8: Muon (a) energy spectra and (b) angular distributions of ν_μ interactions in MRD iron plates for each month.

The pion monitor measurements were performed at the beginnings of June and November, 1999.

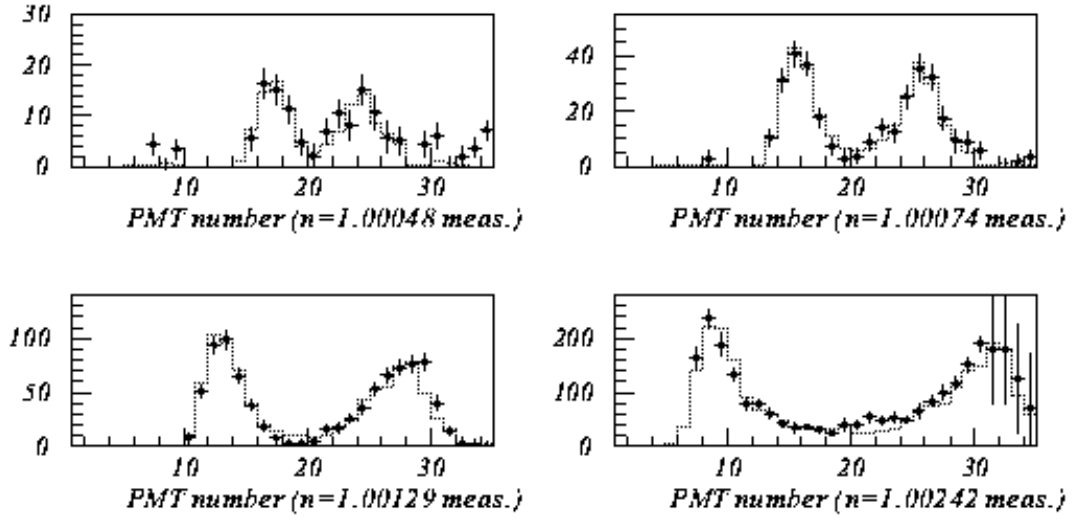


Figure 9: Cherenkov photon distributions measured by the pion monitor. The points with error bars show data and the histograms show the fit results.

The measured photon distributions on the PMT array are shown in Fig. 9 with the fitted results for some of indices of refraction. Fig. 10(Top) shows the neutrino energy spectral shape at the near site inferred from the pion monitor measurements along with the beam simulation result. The beam simulation is validated by the pion monitor measurement very well. Fig. 10(Bottom) shows the far-to-near flux ratio. The data points are derived from the pion monitor measurement and the lines are the beam simulation results. They show very good agreement.

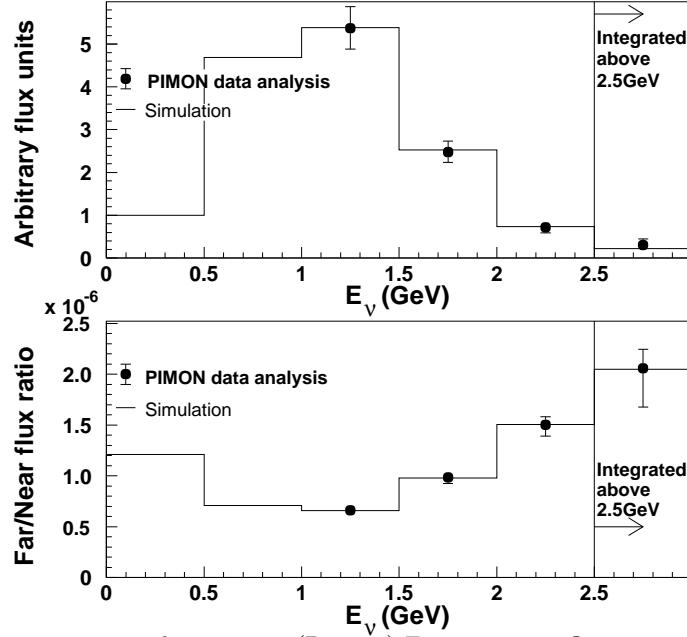


Figure 10: (Top) ν_μ energy spectrum at the near site (Bottom) Far-to-near ν_μ flux ratio. The histograms are from the beam simulation results. The data points are derived from the pion monitor measurement.

Based on these stability measurements and the pion monitor measurement, the expected number of events at SK can be calculated reliably. We obtained $37.8 \pm 0.2(\text{stat})^{+3.5}_{-3.8}(\text{sys})$ based on the 1kt normalization. The sources of the systematic error are the uncertainty of the far-to-near ratio of 6-7% coming from the pion monitor measurement, the uncertainty due to the 1kt measurement of 5% coming mainly from the fiducial volume error and the uncertainty due to the SK measurement of 3%, also coming mainly from the fiducial volume error. Calculations based on the MRD events and the SCIFI events give $41.0^{+6.0}_{-6.6}$ and $37.2^{+4.6}_{-5.0}$, respectively, which are consistent with the number obtained from 1kt.

For the SK event analysis, data reduction similar to that used in atmospheric neutrino analyses is applied. The criteria are: 1) There is no detector activity within 30 μsec before the event. 2) The total collected photo-electrons in a 300 nsec time window is larger than 200. 3) The number of PMTs in the largest hit cluster in the outer-detector is less than 10. 4) The deposited energy is larger than 30 MeV. 5) The reconstructed vertex is at least 2 m inside the wall, which defines the fiducial volume of 22.5 kt. The overall detection efficiency of SK is 79% including neutral current interactions. The inefficiency is mainly due to the energy cut. Accelerator-produced neutrino events at SK are selected by using GPS time information. The distribution of the time difference between the SK trigger time and the KEK-PS beam spill start time at various reduction stages is shown in Fig. 11(Left). After all of the event selection cuts, the Δt distribution is consistent with the beam spill time of 1.1 μsec and GPS resolution of about 100 nsec. A typical SK event caused by an accelerator-produced neutrino is shown in Fig. 11(Right). We observed 28 fully contained (FC) events in the SK fiducial volume. The expected background from atmospheric neutrinos is less than 10^{-3} events. The observed numbers of events at SK are compared with the expected numbers in each event category in Table 1.

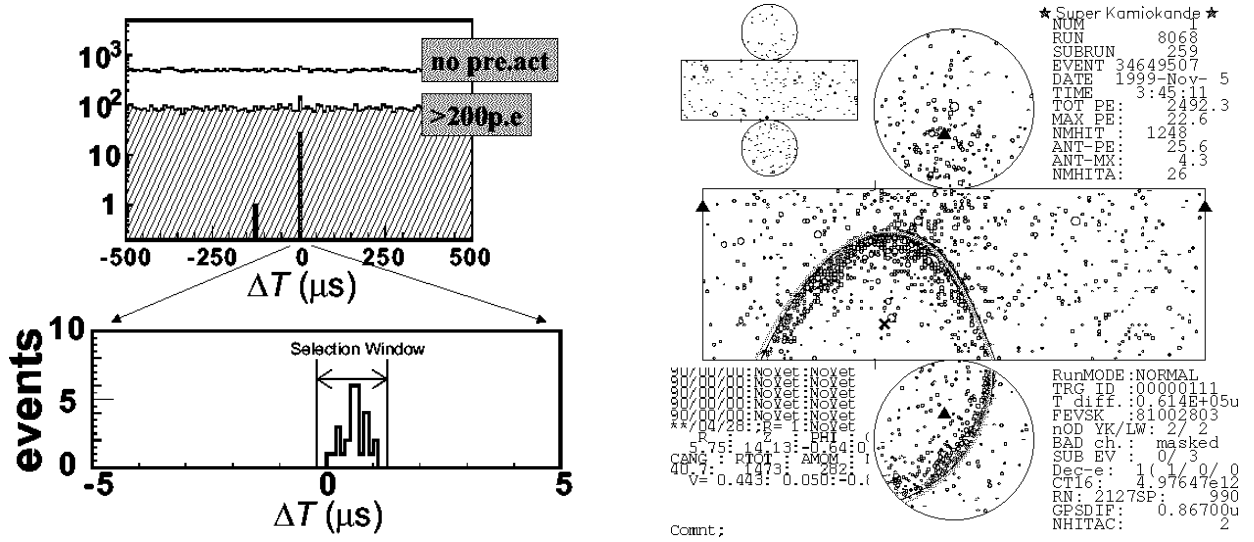


Figure 11: (Left) ΔT distribution. (Right) Candidate of FC single ring μ -like event in the fiducial volume.

Table 1: Breakdown of the observed and expected numbers of events into event categories.

Category	Obs.	Expected
1-ring μ -like	14	20.9
1-ring e-like	1	2.0
multi rings	13	14.9
Total	28	$37.8^{+3.5}_{-3.8}$

The visible energy (electron equivalent energy) distribution of the selected 28 events is shown in Fig. 12 together with the MC expectation. The systematic error of the MC expectation is under study. The visible energy distribution and the angular distribution with respect to the KEK direction of the 1-ring μ -like events are shown in Fig. 13.

4 Conclusions

The method of a long-baseline neutrino experiment has been established, namely beam steering, monitoring the neutrino beam at the near site, predicting neutrino properties at the far site from the near site measurements and time synchronization between the near site and the far site. In the data taken from June 1999 to June 2000, corresponding to 2.29×10^{19} protons on target, we observed 28 FC events in the fiducial volume of SK, while the expected number without oscillation was 37.8 with an

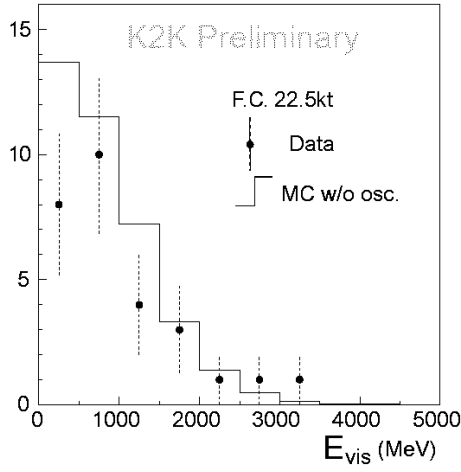


Figure 12: Visible energy distribution of the selected FC events in the SK fiducial volume.

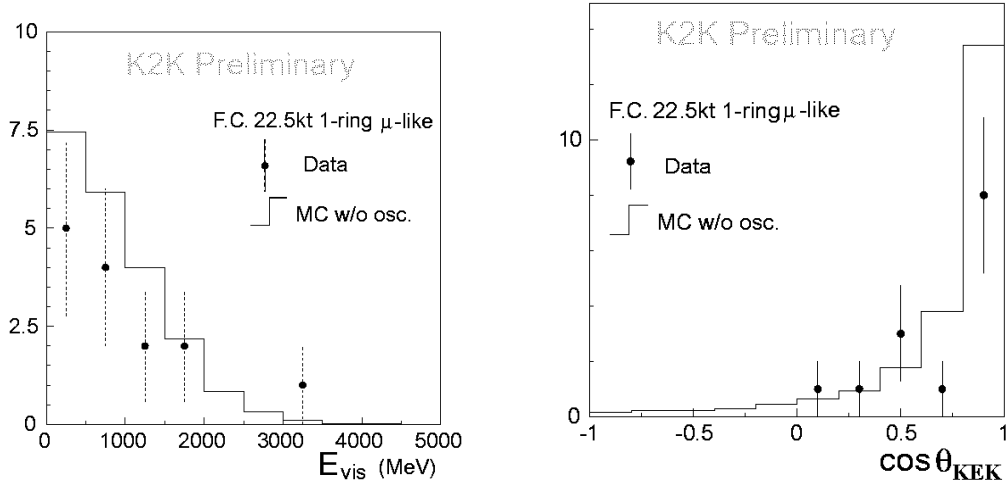


Figure 13: (Left) Visible energy distribution of the 1-ring μ -like FC events in the SK fiducial volume. (Right) Angular distribution with respect to the KEK direction of the 1-ring μ -like FC events in the SK fiducial volume.

error of about 10%. This means that the deficit of ν_μ in the 1-GeV energy region after 250-km flight was observed at the 90% significance.

We aim to accumulate data corresponding to at least 10^{20} protons on the target and to perform a spectral analysis to see the characteristic energy distortion in the case of neutrino oscillation. We will also study the ν_e appearance. The experiment resumed in January 2001 and we are taking data until July for this year.

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